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ESTIMATION OF AGING EFFECTS OF PILES IN MALAYSIAN OFFSHORE LOCATIONS

JERIN M. GEORGE*, M. M. A. WAHAB, KURIAN V. JOHN

Universiti Teknologi PETRONAS, Bandar Seri Isakandar, Tronoh, 31750, Perak, Malaysia
*Corresponding Author: jerinmplathottam@gmail.com

Abstract

An increasing demand for extending life and subsequently higher loading requirements of offshore jacket platforms are among the key problems faced by the offshore industry. The Aging effect has been proved to increase the axial capacity of piles, but proper methods to estimate and quantify these effects have not been developed. Borehole data from ten different Malaysian offshore locations have been analysed and they were employed to estimate the setup factor for different locations using AAU method. The setup factors found were used in the Skov and Denver equation to calculate capacity ratios of the offshore piles. The study showed that there will be an average improvement in the axial capacity of offshore piles by 42.2% and 34.9% for clayey and mixed soils respectively after a time equal to the normal design life (25 years) of a jacket platform.

Keywords: Aging effect of piles, Setup factor, Offshore piles and offshore jacket platforms.

1. Introduction

Increasing demand for extending the life of jacket platforms due to further oil and gas discoveries and Enhanced Oil Recovery (EOR) and following that higher loading requirement on the platforms from the modifications and work over demands are the common problems faced by the Malaysian offshore industry. Currently, Petronas Carigali Sdn Bhd (PCSB) has more than 150 operating platforms in the domestic waters of Malaysia. About 60% of the platforms have been in operation for more than 20 years, 20% have already exceeded 30 years with several other nearing their initial design life of 20-25 years. When undertaking reliability assessments on the aged platforms, PCSB have found out that the factor of safety for pile foundation capacity is very low [1].

The capacity of a pile is expected to increase with time due to aging effects. A

Nomenclatures

B	A similar factor like Δ_{10} used in Eq. (6)
I_p	Plasticity index
Q_{14}	The pile capacity at 14 days, N
Q_{EOD}	The instantaneous capacity at the end of driving of the pile, N
Q_o	Axial capacity of pile at the reference time t_o, N
Q_t	Axial capacity of pile at time t after driving, N
S_t	Sensitivity of soil
S_{uu}	Undrained shear strength of the soil, N/m^2
t	Time corresponding to Q_t, s
t_{eoc}	Time for end of consolidation, s
t_o	The reference time at which Q_o is measured, s

Greek Symbols

Δ_{10}	Setup factor

Abbreviations

AAU	Aalborg University
API	American Petroleum Institute
EOR	Enhanced Oil Recovery
NGI	Norwegian Geotechnical Institute
OCR	Over Consolidation Ratio
PCSB	Petronas Carigali Sdn Bhd

proper understanding and quantification of these aging effects is not available. So while doing the re-assessment, PCSB used the original or young platform capacity from the API recommendations. If the platforms can be re-assessed with the improved pile capacity considering the aging effects, it will help to have more factor of safety for pile foundation capacity. This will in turn allow jacket platforms in Malaysia to have more operating life or to have higher loadings than they were designed for. Hence, the study aims to identify the proper method for quantifying the aging effects of piles and to use those methods to predict the aging effects of piles in Malaysian Offshore locations.

2. Theoretical Background

The capacity of piles is known to be changing with time. The correct mechanisms behind these changes have not been fully understood. Researchers have been trying to study the mechanisms behind the change in capacity of piles and represent them as mathematical equations known as 'time functions for capacity of piles'.

The change in capacity of a pile can be positive (increase) or negative (decrease) according to the conditions of the pile and the soil strata in which the pile is installed. An increase in capacity is known as 'Setup' and decrease in capacity is known as 'Relaxation'. Relaxation is a rarely observed phenomenon.

2.1. Mechanisms behind relaxation

Relaxation is observed in piles, but fortunately much less often than setup. Also the conditions favouring relaxation are absent in offshore Malaysian locations. The mechanisms behind relaxation can be any of the following:

- Sands confined by a cofferdam or closely spaced piles, in which the lateral confining stress may relax [2].
- Chemical deterioration of the soil at the pile toe due to the presence of water introduced during the pile installation [3].
- Gradual cracking of rock underneath the pile toe due to very high contact stresses under the pile toe [3].
- Strong soils (e.g., dense fine sands) that dilate during pile penetration, creating negative pore pressure that later dissipate [2].

2.2. Mechanisms behind setup

Setup can be classified into two sub categories for ease of understanding:

2.2.1. Long term effects or aging effects

The gain in capacity after end of consolidation is known as long term effects or aging effects and it can be the result of a combination of mechanisms such as [4]:

- Increase in the earth pressures against the pile surface on the long term, due to creep of the soil structure.
- Long-term build-up of new diagenic bonds between soil particles, after the complete destruction of the soil structure due to the severe displacements and disturbance resulting from the driving of the pile into the ground.
- Chemical bonding due to the interaction between the steel pile surface and the soil minerals (cation exchange).
- Effects of sustained loads on the piles, gradually causing a more stable soil structure and increased strength.
- Effects of previous loading and unloading cycles of the piles, which can have similar effects as sustained loading.

2.2.2. Short term effects

The gain in capacity from the end of driving of pile to the end of consolidation phase is known as short term effects. It can be explained by the following mechanisms:

- Equalisation of excess porewater pressure built up during driving (also known as consolidation) [5].
- All aging mechanisms as described above.

2.3. Phases in setup

Three phases in the process of setup have been explained by Komurka et al. [6] as follows:

Logarithmically Nonlinear Rate of Excess Porewater Pressure Dissipation - (Phase 1)

The rate of dissipation of excess porewater pressure is non-linear with respect to the log of time for some period after driving because of the highly disturbed state of the soil. This first phase of set-up has been demonstrated to account for capacity increase in a matter of minutes after installation. In clean sands, the logarithmic rate of dissipation may become linear almost immediately after driving (say 1 day). In cohesive soils, the logarithmic rate of dissipation may remain non-linear for several days (10 days).

Logarithmically Linear Rate of Excess Porewater Pressure Dissipation - (Phase 2)

A short while after driving, the rate of excess porewater pressure dissipation becomes constant (linear) with respect to the log of time. During this phase, the affected soil experiences an increase in effective vertical and horizontal stress, consolidates, and gains shear strength according to conventional consolidation theory. As with the first phase after driving, the duration of the logarithmically constant rate of excess porewater pressure dissipation is a function of soil and pile properties. The combination of all mechanisms in Phase 1 and Phase 2 are collectively called as short term effects.

Aging - (Phase 3)

For a consolidating soil layer, conventional consolidation theory holds that infinite time is required for dissipation of excess porewater pressure to be complete. Practically speaking, there is a time after which the rate of dissipation is so slow as to be of no further consequence, at which time it is accepted that primary consolidation is complete. However, secondary compression continues after primary consolidation is complete, and is independent of effective stress and this referred as aging. The mechanisms behind the aging process are as mentioned earlier and it creates the pile capacity increase at a rate approximately linear with the log of time.

These three phases of setup are schematically illustrated by Komurka et al. [6] in Fig. 1. The illustration of the setup in pile capacity is valid only if the soil conditions are uniform along the shaft length and below the toe. If different layers of soil are present (most of the practical cases), different rates of setup will become effective for each layer.

2.4. Time functions

Many mathematical relations describing the gain in capacity of piles with respect to time after installations have been proposed by different researchers. Some of the relevant equations are discussed below.

Skov and Denver

By far the most popular relationship was presented by Skov and Denver, which models setup as linear with respect to the log of time. They proposed a semi-logarithmic empirical relationship to describe setup as:

$$Q_t/Q_o = 1 + \Delta_{10}\,[\log(t/t_o)] \tag{1}$$

where, Q_t is the axial capacity at time t after driving, Q_o is the axial capacity at the reference time t_o, Δ_{10} is the setup factor, a constant depending on soil type and t_o is the reference time at which Q_o is measured. According to Skov and Denver (1988), the values of Δ_{10} in Eq. (1) for piles located in sand, clay and chalk are 0.2, 0.6 and 5.0, respectively. Correspondingly, the reference time, t_o, is assumed to be 0.5, 1.0 and 5.0 days. These values of $t_{o,}$ will ensure a stabilized increase of the capacity with time. Before this, the pore pressure has not reached the stationary state and soil remoulding continues to take place. Furthermore, Skov and Denver point out that there should be an upper limit to t for which Eq. (1) is used. However, no guidelines are given for this upper limit [7].

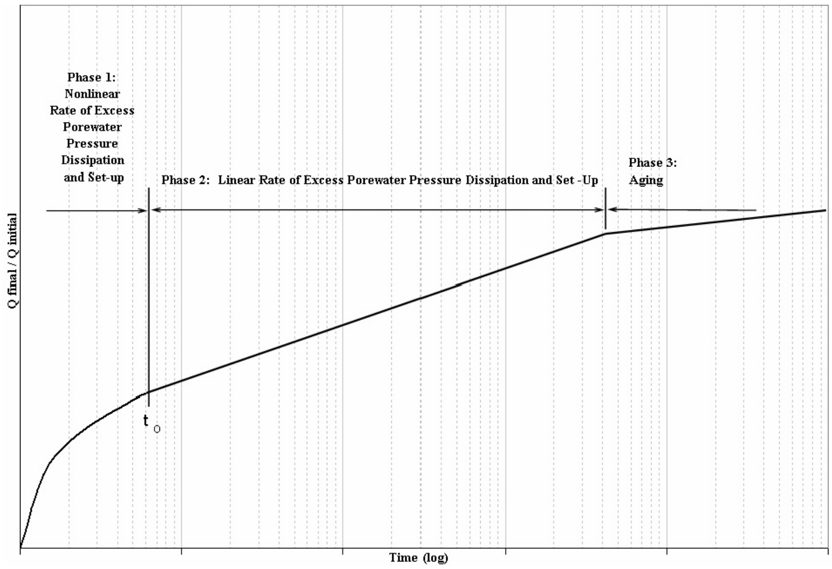

Fig. 1. Idealized schematic of setup phases [6].

Svinkin

Svinkin developed a formula for set-up in sands based on load test data.

$$Q_t = 1.4Q_{EOD}.t^{0.1} \quad \text{upper bound} \tag{2}$$

$$Q_t = 1.025Q_{EOD.}t^{0.1} \quad \text{lower bound} \tag{3}$$

where, Q_{EOD} is the instantaneous capacity at the end of driving of the pile [8].

Guang-Yu

Guang-Yu presented an equation for capacity of piles driven into soft soils. Guang-Yu suggested that sands and gravels experience no set-up.

$$Q_{14} = (0.375S_t + 1).Q_{EOD} \tag{4}$$

where, Q_{14}=pile capacity at 14 days S_t=sensitivity of soil [9].

Svinkin and Skov

Svinkin and Skov presented a variation of Eq. (1), using t_o = 0.1 day.

$$Q_t/Q_{EOD} - 1 = B[\log_{10}(t) + 1] \quad (5)$$

where, Q_t is ultimate resistance at time = t days, Q_{EOD} is end of driving resistance, B is a similar factor like Δ_{10} in Eq. (1) [10].

Unlike the Skov and Denver relationship, the other formulae all include the instantaneous capacity at end of driving, Q_{EOD}, which can be determined by dynamic monitoring of driving. So the use of the other equations will become possible only in case the Q_{EOD} is known already.

2.5. Modifications and improvements in the Skov and Denver Equation

Many researchers and research organisations have been working on modifying and improving the original Skov and Denver equation. Some have conducted experimental study to find the constants in the equation particular to a certain type of soil or regional conditions. Some of the notable works in this area are included in the following section.

Assumption of the reference time, t_0

The reference time is the time at which the capacity of a pile is known to us. There are many ways to find out pile capacity namely:

a. Static Design equations
b. Pile Driving Formulae
c. Static Loading test
d. Stress Wave Analysis

Out of the above said methods, only static design equations and pile driving formulae will have problem with finding out its reference time. In other methods, the reference time is the time gap between end of driving and the testing. While using pile driving formulae, t_0 =0.25 days (6 hours) is commonly used. If a time longer than 6 hours is required for pile driving, then it can be used as t_0.

The reference capacity, Q_0 can be determined by some static design equations such as the procedure proposed by the American Petroleum Institute (API, 1993) or the NGI method developed by the Norwegian Geotechnical Institute. The capacity predicted by the above said methods uses the soil properties prior to driving. So the capacity will be different from Q_{EOD}. By choosing a small value of t_0 as originally proposed by Skov and Denver may not give correct predictions if we are using static design equations to find Q_t. In these circumstances, use of t_0 = 100 days while using Skov and Denver equation will become appropriate [5].

Difference in predicting long term and short term effects

Augusteen et al. [5] proposed different Δ_{10} values for long and short term effects. Short term effects regarding the capacity of piles are related to both real time aging and the equalisation of excess pore pressures built up during driving. In contrast, long term effects are only due to aging. Hence, different values of Δ_{10}

are expected when either short or long term effects are investigated. If setup is considered, the short-term component of Δ_{10} is greater than the long term component, i.e. Δ_{10} short-term > Δ_{10} long term as shown in Fig. 2. When relaxation takes place, Δ_{10} short-term becomes negative.

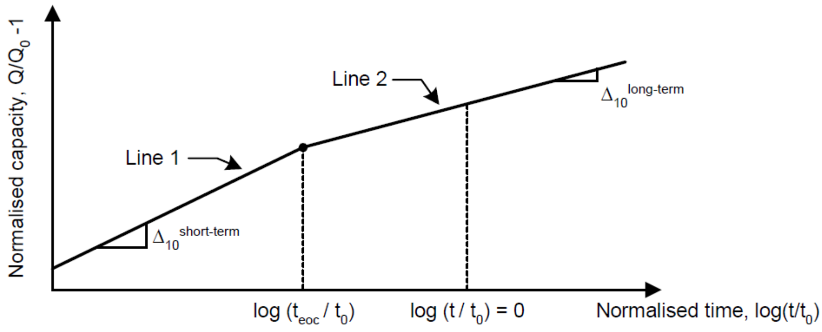

Fig. 2. Influence of short term and long term effects on Δ_{10}.

The time for equalisation of pore pressure or end of consolidation is denoted by t_{eoc}. It should be noted that both Δ_{10} and Q_0 depend on whether $t < t_{eoc}$ or $t > t_{eoc}$ [5].

Estimation of correct setup factor or Δ_{10}

Originally Skov and Denver proposed fixed Δ_{10} values for clay and sand. Clausen and Aas [11] postulated that the long term setup depends on the soil properties. The Δ_{10} or setup factor is introduced as a function of the plasticity index (I_p) and the over consolidation ratio (OCR).

$$\Delta_{10} = 0.1 + 0.4(1 - I_p/50).OCR^{-0.8} \tag{6}$$

$$0.1 \leq \Delta_{10} \leq 0.5$$

Equation (7) is based on very few tests. The reference time, t_0 is chosen as 100 days. The time function based on Eq. (7) is denoted NGI because it has been developed at the Norwegian Geotechnical Institute. Augusteen et al. [5] postulated that the form of Δ_{10} that best fits the observed behaviour from experimental data (mostly obtained from NGI) is as follows:

$$\Delta_{10} = 1.24 - (S_{uu}/60)^{0.03} \tag{7}$$

where, S_{uu} is the undrained shear strength of the soil. The equation relating Δ_{10} to S_{uu} is named as AAU (after Aalborg University where it was developed) [5].

If different layers of soil are present, NGI has proposed to take the average values of I_p, OCR and S_{uu} to determine the Δ_{10} for a pile. But Augusteen et al. [5] have proposed two different ways which may be more accurate than NGI proposal.

a) Option 1: Eq. (1) is applied to every single soil layer using Δ_{10} found out using I_p, OCR and S_{uu} of that particular layer.
b) Option 2: Eq. (1) is used for the entire pile. This implies that an average value of I_p, OCR and S_{uu} must be estimated for the soil surrounding the pile.

Unlike the NGI's proposal, Augusteen et al. [5], proposes to use mean values by weighting the soil parameter by surface area or weighting the soil parameter by the calculated capacity of the different layers by means of static design equations.

The above said equations for Δ_{10} are applicable only when the soil is cohesive in nature. There are no equations available for finding out Δ_{10} corresponding to non-cohesive soils (sands) [12]. So we will have to use the original constant Δ_{10} proposed by Skov and Denver for piles in non-cohesive soils.

Type of capacity predicted

The Skov and Denver equation was developed using combined resistance data (lumping side shear and toe resistance). Bullock et al. proposed use of the original equation for side shear capacity only and found out Δ_{10} in the range 0.1 to 0.32 [13,14].

2.6. Critical aspects of aging effects of piles in offshore locations

The mechanisms expected to create the aging effects of piles in the axial direction can create some effect in the lateral direction of the piles too, thus creating lateral aging effects. The theoretical background study done above was unsuccessful in revealing any literature which have references in the following direction. If the lateral aging effects are found to be present, it is going to create a huge impact in the offshore industry, but the scope of this paper does not cover this aspect.

The offshore piles are all steel friction piles with minimum or negligible toe resistance. So most of the mechanisms of relaxations will become null or void in offshore conditions. Thus the relaxation effects become irrelevant for the rest of study.

The Skov and Denver equation is by far the most reliable method of prediction of setup in piles. Other time functions mentioned in the literature review uses end of driving capacity which is rarely or not available in offshore piles, which restricts the scope of working with them. Some of the literatures have not considered the long term and the short term effects separately. Proper care should be given in analysing or using such results so as to reduce the error in the work.

The static design equations stated by API are used to find the reference capacity of the piles of offshore jacket platforms. The soil properties which are obtained from borehole data are being used to determine the pile capacity. So Augusteen et al.'s proposal [5] to use the reference time t_0 = 100 days can be accepted. While the pile is driven, the soil is remoulded and it is expected that the soil will reach its initial conditions after 100 days. Some researchers have stated that this time is time in which consolidation or short term effects cease to exist. The consolidation phase is expected to be less than 100 days in most cases. So the assumption of t_0 = 100 days can be justified as a certain safety factor.

According to researchers, the piles in Malaysian onshore soil conditions have experienced aging effects, but there are no published studies which have looked into the offshore soil conditions or the aging effects of offshore piles in Malaysia. This can be attributed to the facts that the offshore soil data is rarely available and the impossibility of conducting experimental studies on offshore piles. The difficulties faced by the Malaysian offshore industry are not limited to the region but are effective globally. So this study is trying to bridge this gap with the numerical methods to predict the aging effects of Malaysian offshore piles and at the same time demonstrating a method which can be utilised in similar conditions elsewhere.

3. Soil Data Analysis to Estimate the Setup Factor

Soil data from ten Malaysian offshore borehole locations were obtained. The map showing these locations is given in Fig. 3. Malaysian offshore waters are divided into three regions, namely Peninsula Malaysia Operation (PMO), the waters of east Malaysia near Terengganu, Kelantan and Pahang; Sabah Operations (SBO) and Sarawak Operations (SKO) near offshore Sabah and Sarawak respectively; both are from east Malaysia near Borneo. The soil data is selected in such a way that all these three locations are represented properly. The soil data used for the study are the borehole log information collected by PCSB during the exploration of offshore sites prior to installation of platforms.

The methodology adopted for the following soil data analysis can be used as a normal practice for estimation of setup factor of a location from the soil properties. The use of this practise can be adopted universally irrespective of the location conditions (offshore or onshore) and the soil varietiey. Also, this part of the study can be extended furthermore to obtain better results for Malaysian Offshore conditions when more soil data becomes available for researchers.

Fig. 3. Map of offshore Malaysia showing the borehole locations.

The analysis of the data suggested that 50% of the borehole data can be classified as mixed soils and the other 50% as clayey soils. Mixed soils are defined as borehole locations where both sandy and clayey layers are found in comparable abundance whereas clayey soils are defined as borehole locations where clayey layers are found in abundance with negligible presence or absence of sandy layers. A schematic diagram showing the typical borehole strata in Mixed and Clayey soils is given in Fig. 4.

Fig. 4. Schematic diagram showing the typical borehole strata.

The NGI method to find the setup factor was not applicable for the data as most layers did not have I_p values corresponding to them. Even if they had I_p values, they were from only a particular point in the soil layer which cannot be used as a representative value for the entire layer. The AAU method has only the undrained shear strength as the input parameter. Since all clayey layers had undrained shear strength values corresponding to them, the application of the AAU method is suitable for the data. Some layers had a range of shear strength values for them. In those cases, the average value for the layer was used to find the setup factor of that layer. The shear strength value from the particular clayey layer was used in Eq. (7) in order to obtain the setup factor for that layer.

There are no functions for getting the setup factor for sandy layers. So the original constant value given by Skov and Denver were used [7]. The proposed value of Δ_{10} = 0.2 was corresponding to t_0 = 0.5 days. In order to get more accurate results, the normalised Δ_{10} value corresponding to t_0 = 100 days was used.The normalisation method is given by Augusteen et al. [5] as follows:

$$\Delta_{10,1} - \Delta_{10,2} = \Delta_{10,1} * \Delta_{10,2} * \log (t_{0,2}/t_{0,1}) \quad (8)$$

In this study the following values are known: $\Delta_{10,1}$ = 0.2, $t_{0,1}$ = 0.5 days and $t_{0,2}$ = 100 days

$\Rightarrow$ $0.2-\Delta_{10,2} = 0.46\Delta_{10,2}$

$\Rightarrow$ $1.46\Delta_{10,2} = 0.2$

$\Rightarrow$ $\Delta_{10,2} = 0.137$

Therefore by using the normalisation equation the value of $\Delta_{10,2}$ = 0.137 was obtained. This value was used for the sandy layers in the data analysis.

The borehole data from each location was analysed and the setup factor corresponding each layer was found out as mentioned above. The setup factor of a borehole was calculated as the weighted average of the setup factors of different layers weighted over the depth of that particular layer. Also, the average setup factor of a particular type of soil was calculated as the weighted average of borehole setup factors weighted over the borehole lengths.

4. Results and Discussion

The results from the soil data analysis are presented in Table 1. The setup factor for the ten offshore borehole locations was found. The average setup factor for clayey and mixed locations was found out to be 0.215 and 0.178 respectively. The values of the setup factors obtained from this soil data study falls well within the range of the setup factors found out by researchers like Augusteen et al. [5] and Bullock et al. [13,14] in different parts of the world, thus ensuring the acceptability of the values obtained by this study

Table 1. Soil data analysis results.

Location No.	Depth of borehole (m)	General Type of soil	Distribution of different types of soil	Setup Factor (Δ_{10})	Average setup factor
1	190	Clayey	Clay - 99.05% Sand - 00.95%	0.222	0.215
2	150		Clay - 96.20% Sand - 03.80%	0.209	
3	150		Clay - 100.00% Sand - 00.00%	0.217	
4	250		Clay - 100.00% Sand - 00.00%	0.208	
5	150		Clay - 100.00% Sand - 00.00%	0.221	
6	180	Mixed	Clay - 45.89% Sand - 54.11%	0.171	0.178
7	180		Clay - 61.61% Sand - 38.39%	0.181	
8	123		Clay - 48.46% Sand - 51.54%	0.187	
9	150		Clay - 54.53% Sand - 45.47%	0.185	
10	150		Clay - 42.80% Sand - 57.20%	0.171	

4.1. Capacity ratio for clayey soils

The capacity ratio of pile located in the clayey soils are calculated using the Skov and Denver equation, Eq. (1), and the setup factor estimated from the soil data analysis are shown in Table 2. The average setup factor gives an increase in the axial capacity of the pile in clayey soil of 42.2% after the design life of the offshore jacket platform. The maximum and minimum percentages of increase in axial capacity of piles among the five mixed soil offshore locations were observed as 43.5% and 40.8% respectively for a design life of 25 years. The trend of improvement in the axial capacity of offshore piles due to aging effect at different clayey locations and trend of improvement of the average value for clayey soils are shown graphically in Fig. 5.

4.2. Capacity ratio for mixed soils

The capacity ratio of pile located in the mixed soils are calculated using the Skov and Denver equation, Eq. (1), and the setup factor estimated from the soil data analysis are shown in Table 3. The average setup factor gives an increase in the axial capacity of the pile in mixed soil of 34.9% after the design life of the offshore jacket platform. The maximum and minimum percentages of increase in axial capacity of piles among the five mixed soil offshore locations were observed as 36.7% and 33.5% respectively for a design life of 25 years. The trend of improvement in the axial capacity of offshore piles due to aging effect at different mixed locations and trend of improvement of the average value for mixed soils are shown graphically in Fig. 6.

Table 2. Capacity ratio for clayey soils.

t (years)	$\log(t/t_0)$	Q_t/Q_0 (Capacity Ratio) for Clayey Soils					
		L 1	L 2	L 3	L 4	L 5	Average
5	1.262	1.280	1.264	1.274	1.262	1.279	1.271
10	1.563	1.347	1.327	1.339	1.325	1.345	1.336
15	1.739	1.386	1.363	1.377	1.362	1.384	1.374
20	1.864	1.414	1.389	1.404	1.388	1.412	1.401
25	1.961	1.435	1.410	1.425	1.408	1.433	1.422
30	2.040	1.453	1.426	1.443	1.424	1.451	1.439
35	2.107	1.468	1.440	1.457	1.438	1.466	1.453
40	2.165	1.481	1.452	1.470	1.450	1.478	1.465

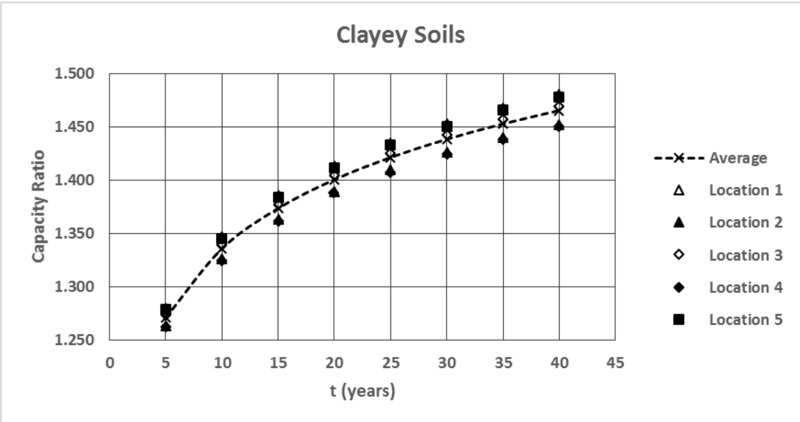

Fig. 5. Improvement of Axial capacity of piles in clayey soils.

Table 3. Capacity ratio for mixed soils.

t (years)	$\log(t/t_0)$	Q_t/Q_0 (Capacity Ratio) for Mixed Soils					
		L 6	L 7	L 8	L 9	L 10	Average
5	1.262	1.216	1.228	1.236	1.233	1.216	1.225
10	1.563	1.267	1.283	1.292	1.289	1.267	1.278
15	1.739	1.297	1.315	1.325	1.322	1.297	1.309
20	1.864	1.319	1.337	1.348	1.345	1.319	1.332
25	1.961	1.335	1.355	1.367	1.363	1.335	1.349
30	2.040	1.349	1.369	1.381	1.377	1.349	1.363
35	2.107	1.360	1.381	1.394	1.390	1.360	1.375
40	2.165	1.370	1.392	1.405	1.400	1.370	1.385

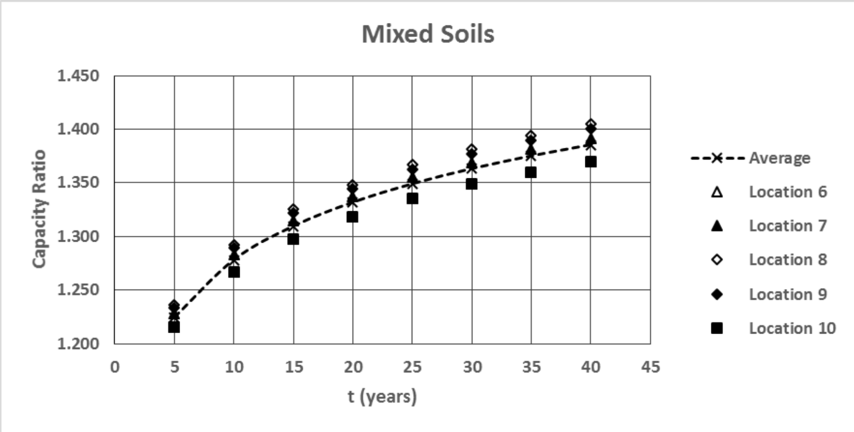

Fig. 6. Improvement of Axial capacity of piles in mixed soils.

5. Conclusions

The study was done in order to identify a proper method to quantify the aging effects of piles in offshore locations. The study recommends the combined use of AAU method and Skov and Denver equation for estimating the aging effects of pile foundations of offshore jacket platforms. The study was able to establish this recommendation which will become very significant in the reassessments for aged offshore jacket platforms. A detailed study of the Malaysian offshore soils was also conducted. Some of the noteworthy conclusions derived from the study are listed down:

- The soil in Malaysian offshore locations can be broadly classified into two categories - Clayey and Mixed.
- The average setup factor for clayey and mixed locations is found out to be 0.215 and 0.178 respectively.
- The average improvement in the axial capacity of offshore piles after a period equal to the normal design life (25 years) of the jacket platform was found to be 42.2% and 34.9% for clayey and mixed soils respectively.
- The effect of aging on the axial capacity of the pile is found to be more pronounced in clayey soils rather than in mixed soils.
- The improvement in the axial capacity of the foundation of a jacket platform can be utilised beneficially to extend the life of the platform.

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